High-resolution modeling and cloud microphysics: Why should we care?

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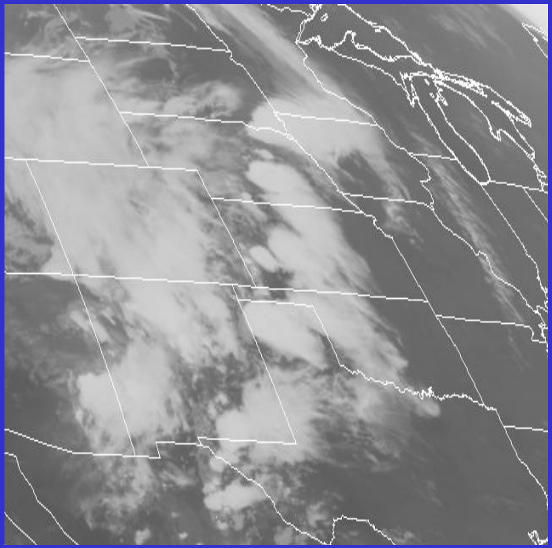
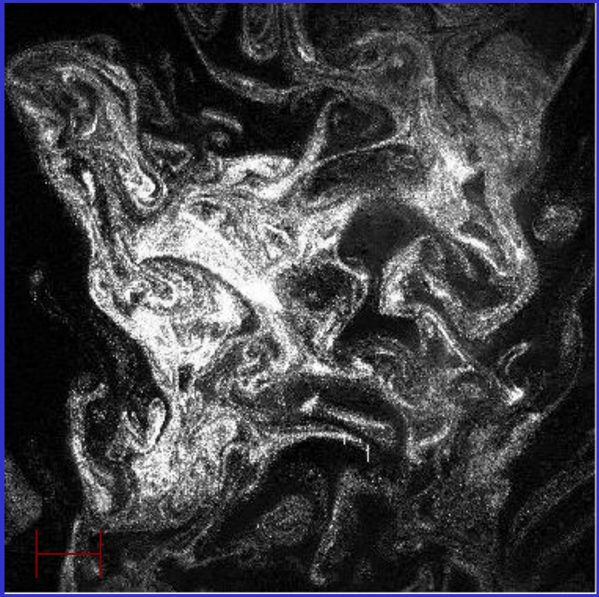
Earth
in visible light

1,000 km

Mesoscale convective
systems over US



Mixing in laboratory
cloud chamber



10 cm

***Clouds and climate:
the range of scales...***

Small cumulus
clouds

“high-resolution modeling”

nonhydrostatic cloud dynamics (i.e., anelastic, compressible, quasi-compressible, etc.)

“microphysics”

processes controlling formation of cloud droplets and ice crystals, their growth and fallout as precipitation

High-resolution modeling and cloud microphysics: Why should we care?

Because of the tight coupling between the cloud microphysics and cloud dynamics, and important effects of cloud microphysics on the atmospheric part of the hydrologic cycle, on radiative processes, on the coupling with the surface, and on cross-tropopause transport.

[N.B.: These are (parameterization)^2 problems if one does not resolve clouds: parameterized microphysics in parameterized clouds…]

- **-Latent heating**
  (condensation.evaporation, sublimation/resublimation, freezing melting)
- **-Condensate loading**
  (mass of the condensate carried by the flow)
- **-Precipitation**
  (fallout of larger particles)
- **-Coupling with surface processes**
  (downdrafts leading to surface-wind gustiness, inject BL with fresh air)
- **-Convective organization**
  (mostly dynamical process, but affected by microphysics, e.g., the strength of a cold pool)
- **-Radiative transfer**
  (mostly mass for absorption/emission of LW, particle size important for SW scattering, size and composition important for SW absorption)
- **-Cloud-aerosol interactions**
  (aerosol affect clouds: indirect aerosol effects, but clouds process aerosols as well)
- **-Transport across tropopause**
  (convective over-shooting, dehydration, etc)
- **- …**

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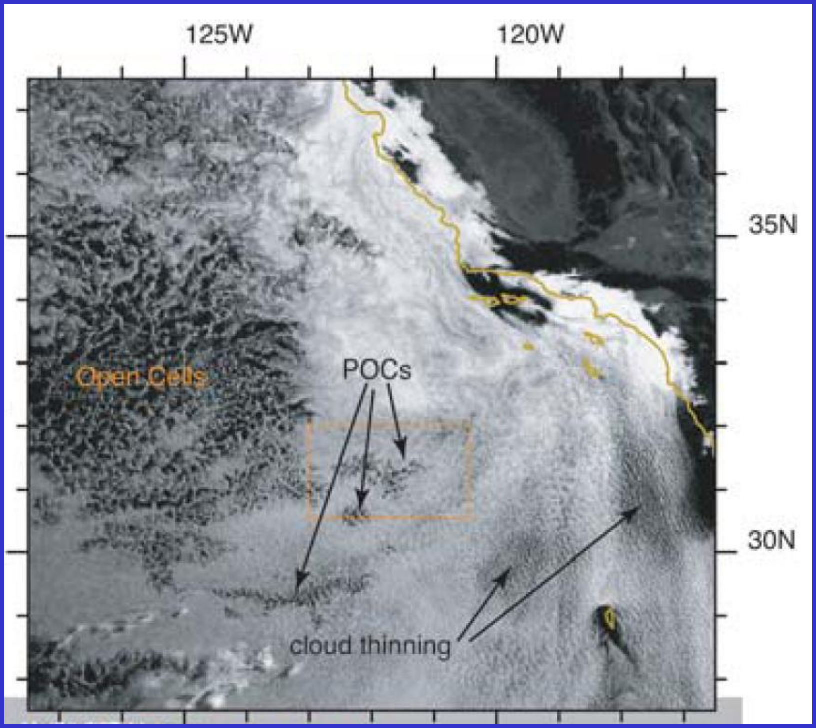

Stevens et al. *BAMS* 1998

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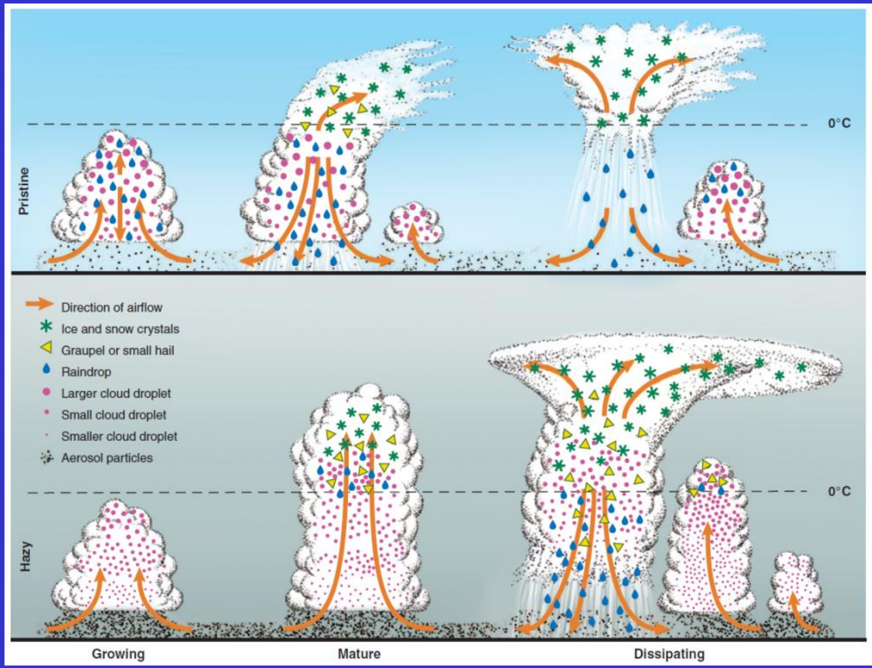

Rosenfeld et al. *Science*, 2008

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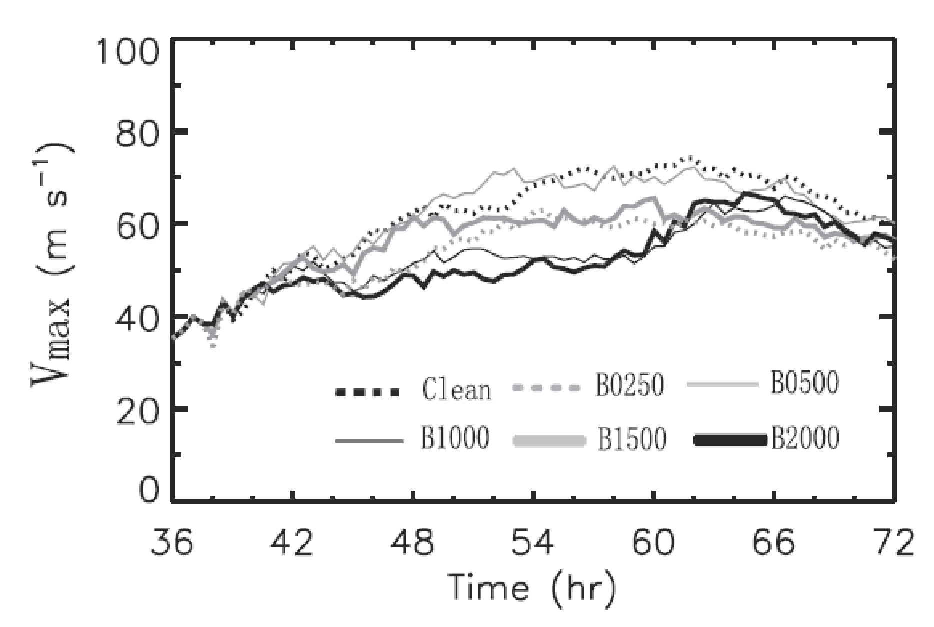
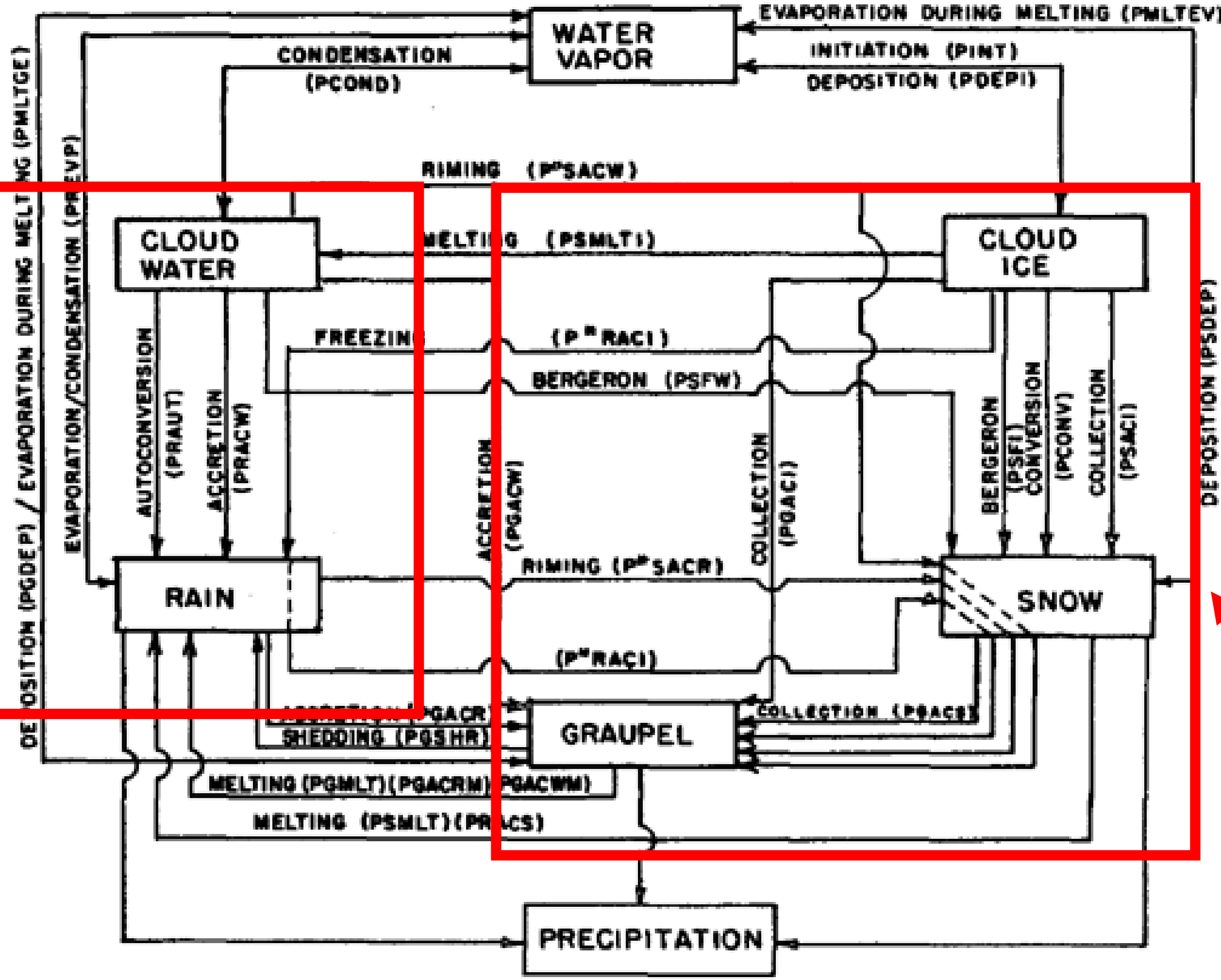


Zhang et al. *GRL* 2009

Examples of hypothesized dynamics-microphysics interactions

Traditional approach to bulk cloud microphysics



Warm-rain part

Ice part

FIG. 1. Schematic depicting the cloud and precipitation processes included in the model for the study of narrow cold-frontal rainbands.

Lin et al. JCAM 1983, Rutledge and Hobbs JAS 1984

So what level of complexity of cloud microphysics scheme is required?

Depends on the particular cloud system:

deep convection:

- the dynamics is the driver, so probably a simple scheme suffices

shallow clouds (especially Sc, maybe shallow Cu):

- dynamics slaved to microphysics, significant fidelity needed.

Modeling studies involving deep convection – convective dynamics as the driver:

early studies of deep convection (late 60ies, early 70ies; UK, US, Japan)
warm-rain microphysics only

early studies of organized convection (70ies, early 80ies; UK, US):
warm-rain microphysics only

super-parameterization (late 90ies)
extremely simple ice (Grabowski) or diagnostic ice (Khairotdinov)

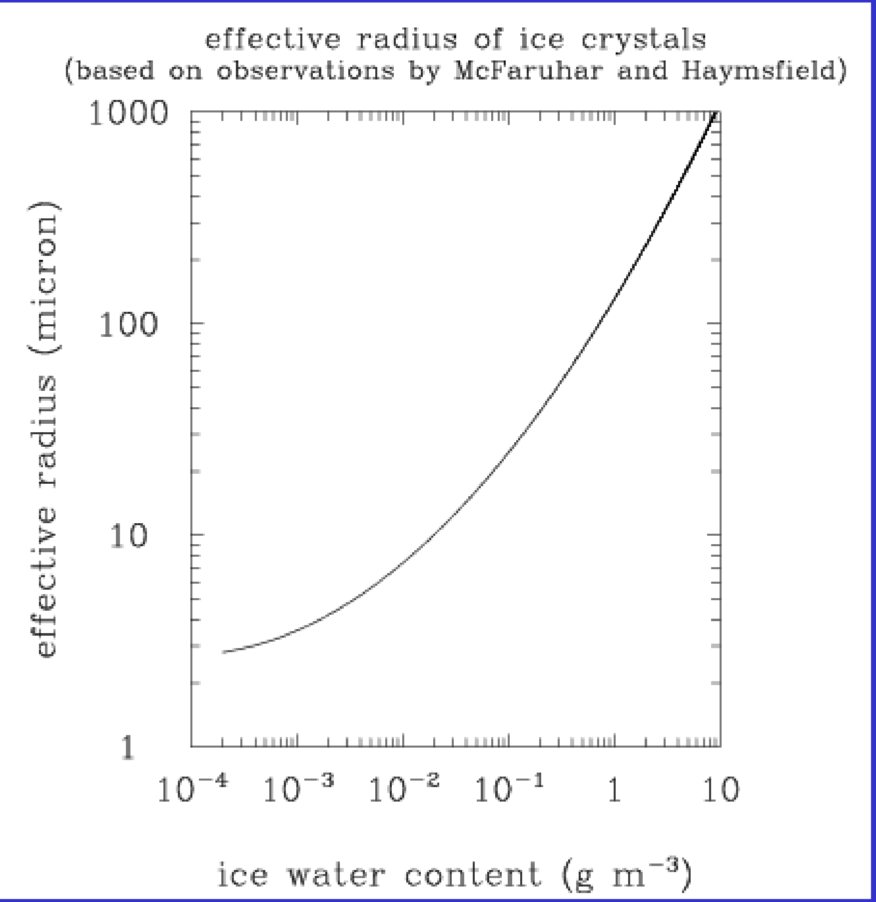
convection-permitting GCM (early 00ies, Japan)
extremely simple ice

But what about radiative transfer? Particle sizes are needed there; effective radius of cloud droplets and ice crystals.

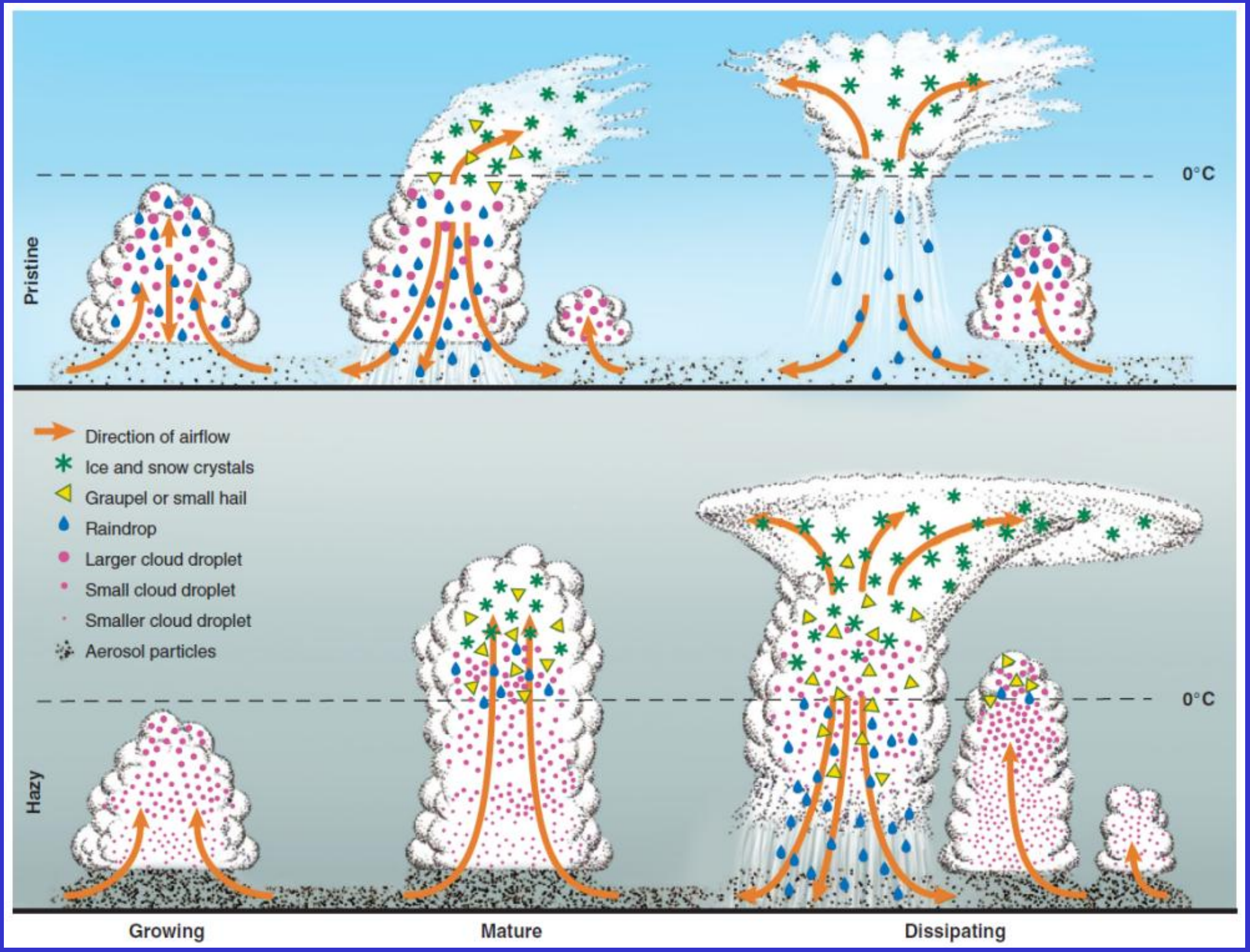
Use observations!

Cloud droplet concentration correlates with aerosol loading (but be careful…)

Ice particle size observed to depend the on mass of ice (again, many caveats…)

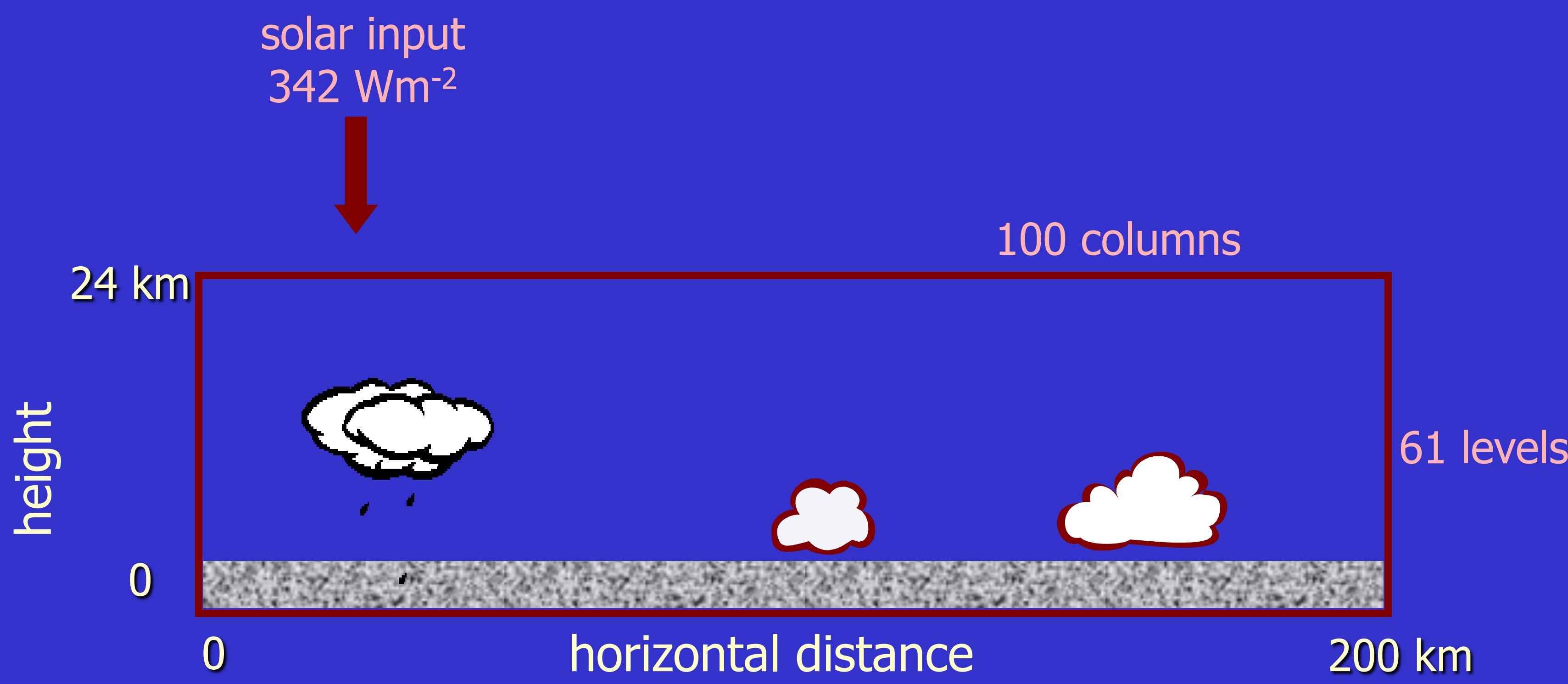


Can deep convection be significantly affected by aerosols?



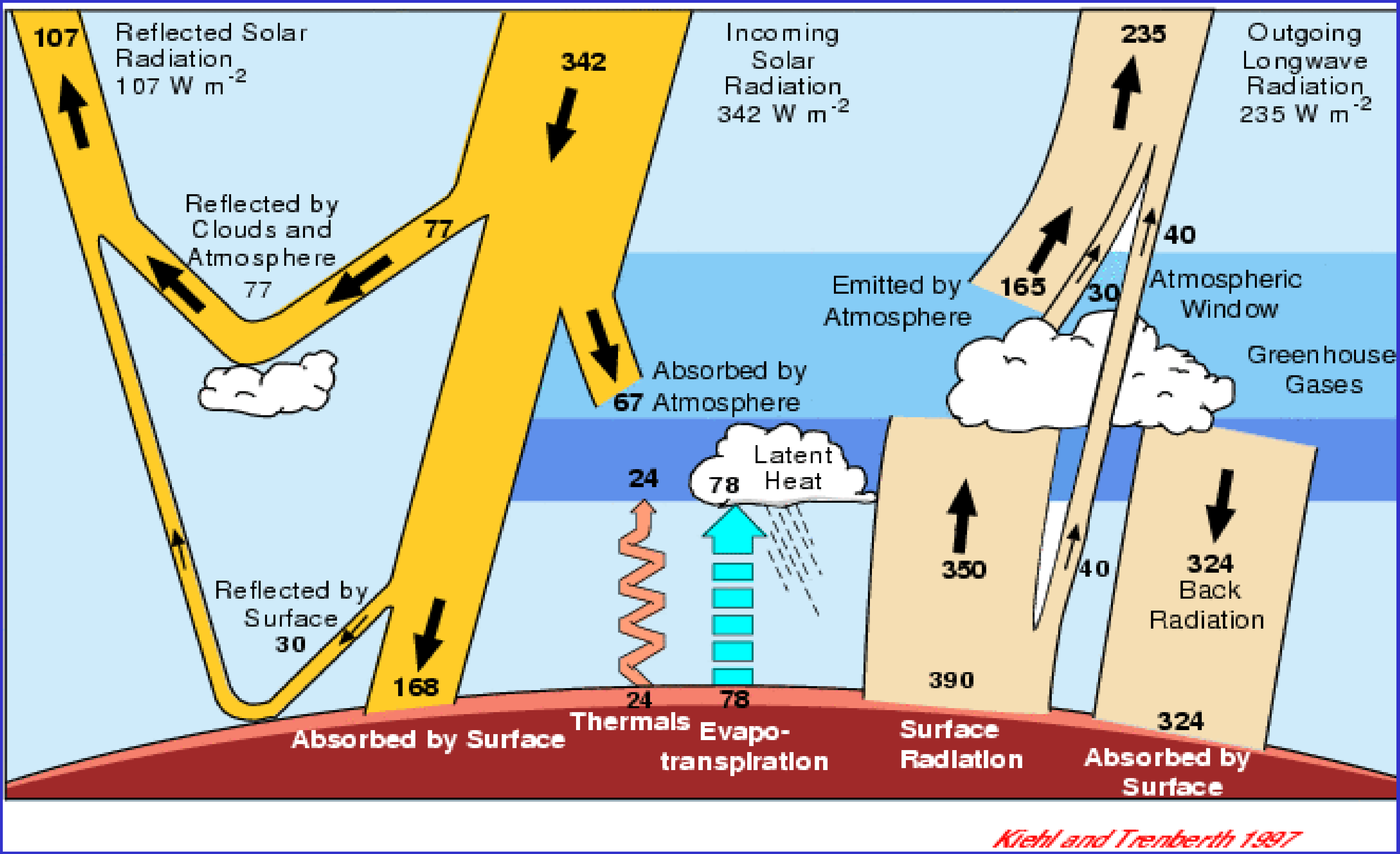
Rosenfeld et al. *Science*, 2008

Radiative-convective quasi-equilibrium mimicking planetary energy budget using a 2D cloud-resolving model



Surface temperature = 15° C
Surface relative humidity = 80%
Surface albedo = 0.15

Grabowski *J. Climate* 2006



The Earth annual and global mean energy budget

Simulations with the new double-moment bulk microphysics:

Warm-rain scheme of Morrison and Grabowski (JAS 2007, 2008a) predicts concentrations and mixing ratios of cloud water and rain water; relatively sophisticated CCN activation scheme with either ***pristine*** or ***polluted*** CCN spectra.

Ice scheme of Morrison and Grabowski (JAS 2008b) predicts concentrations and two mixing ratios of ice particles to keep track of mass grown by diffusion and by riming; heterogeneous and homogeneous ice nucleation ***with the same IN characteristics for pristine and polluted conditions***.

60-day long simulations starting from the sounding at the end of the single-moment simulations of Grabowski (2006).

Traditional approach to bulk cloud microphysics

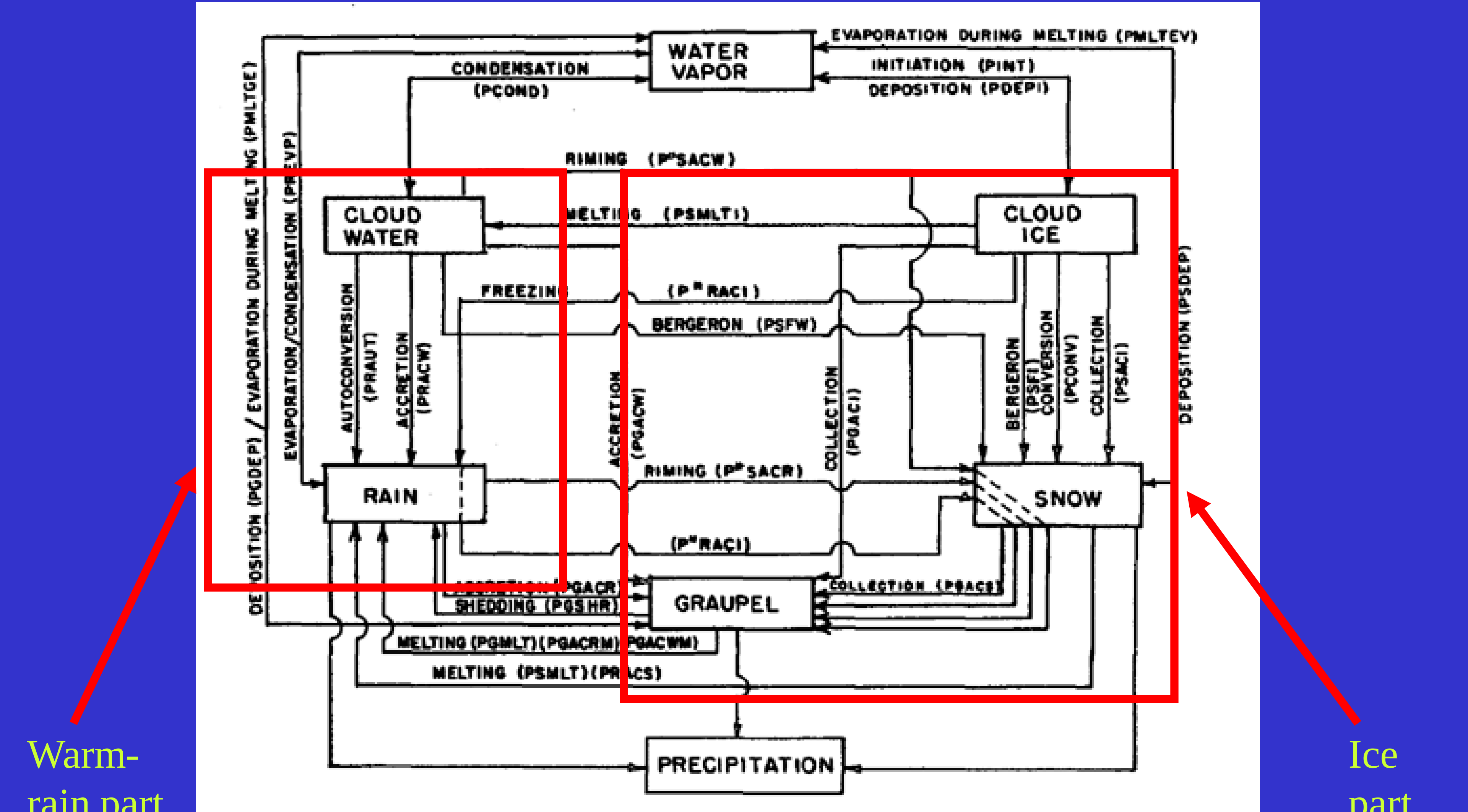
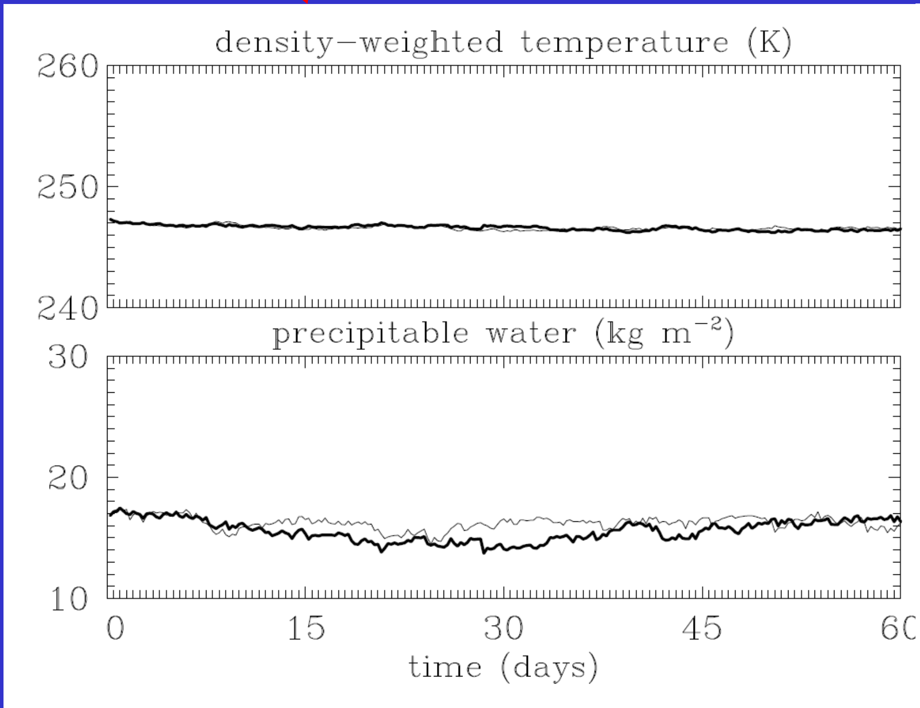


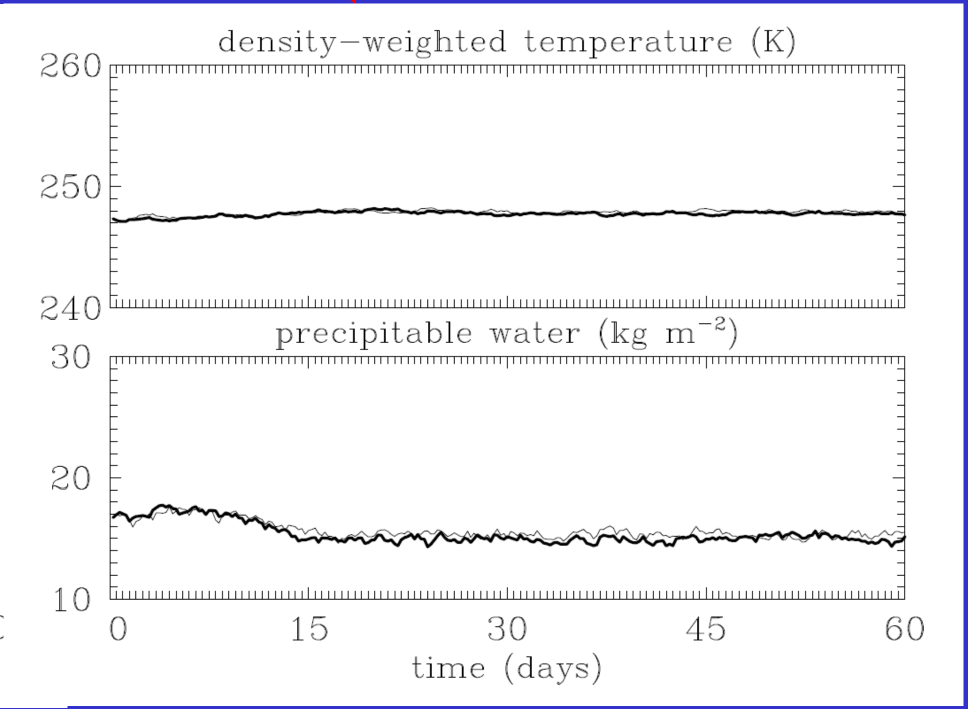
FIG. 1. Schematic depicting the cloud and precipitation processes included in the model for the study of narrow cold-frontal rainbands.

Lin et al. JCAM 1983, Rutledge and Hobbs JAS 1984

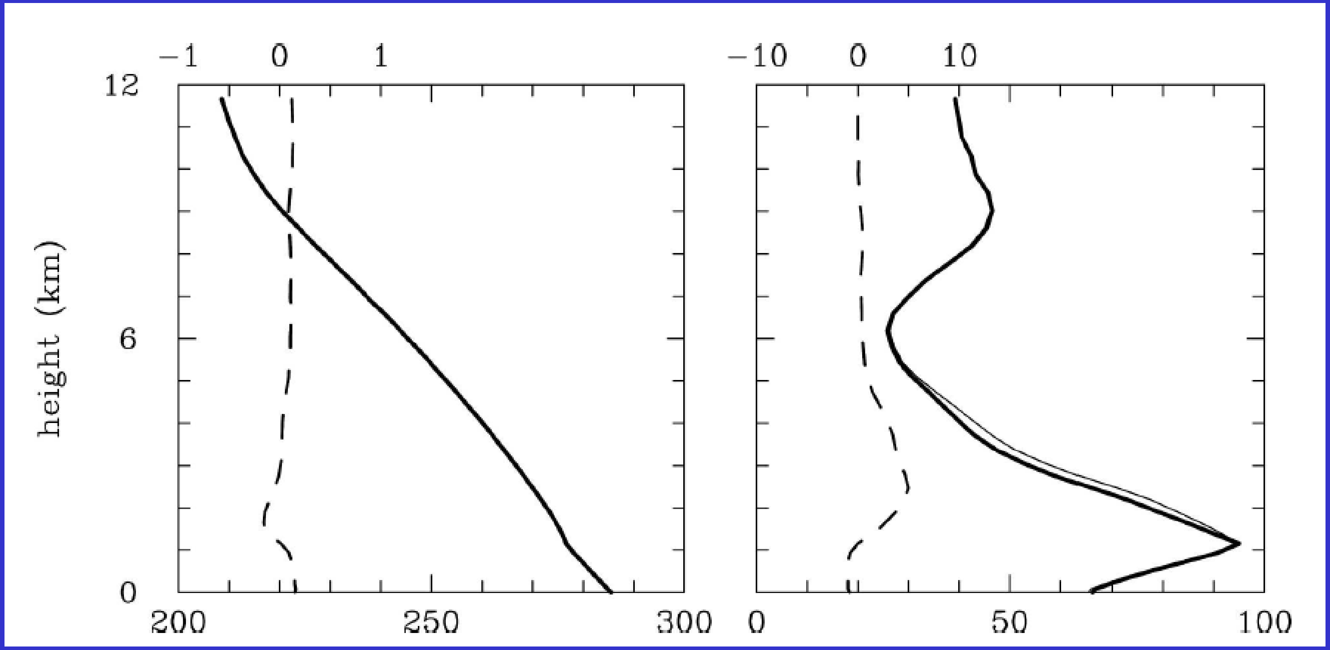
Grabowski *J. Climate* 2006

new simulation



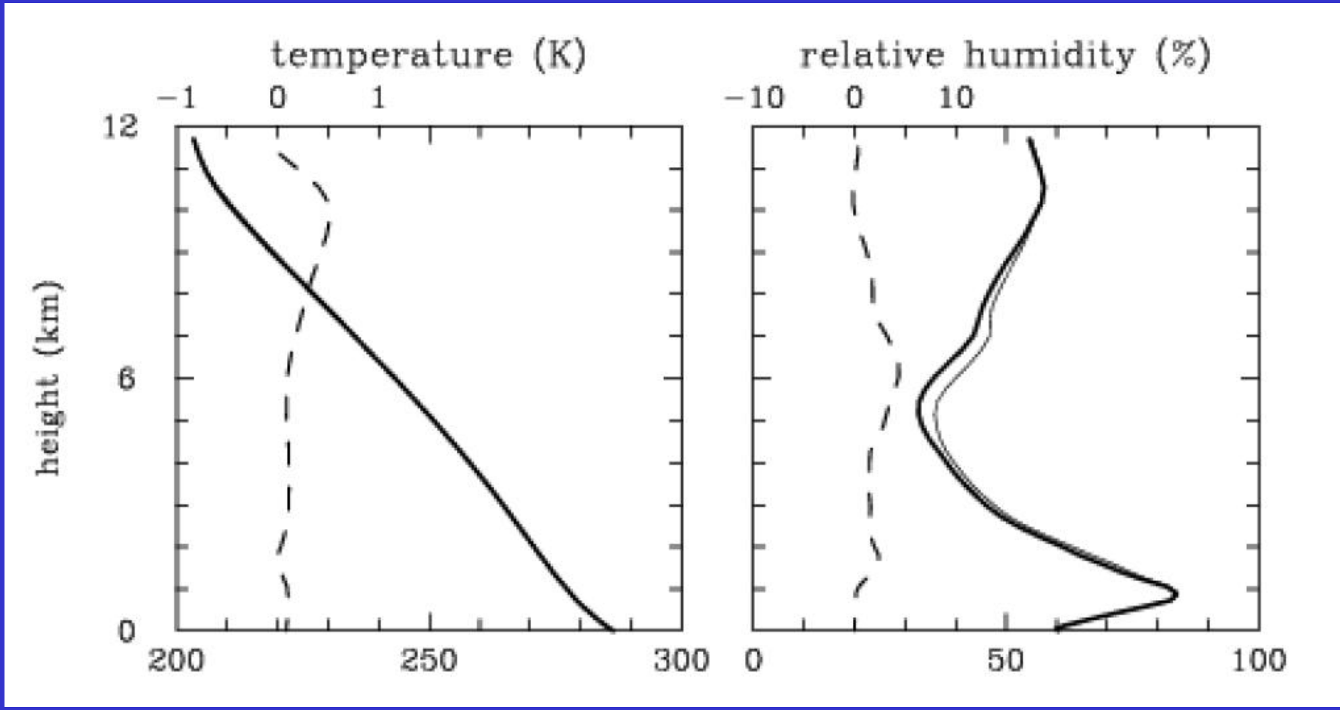


Grabowski
***J. Climate* 2006**



Thin: polluted
Thick: pristine
Dashed: polluted-pristine

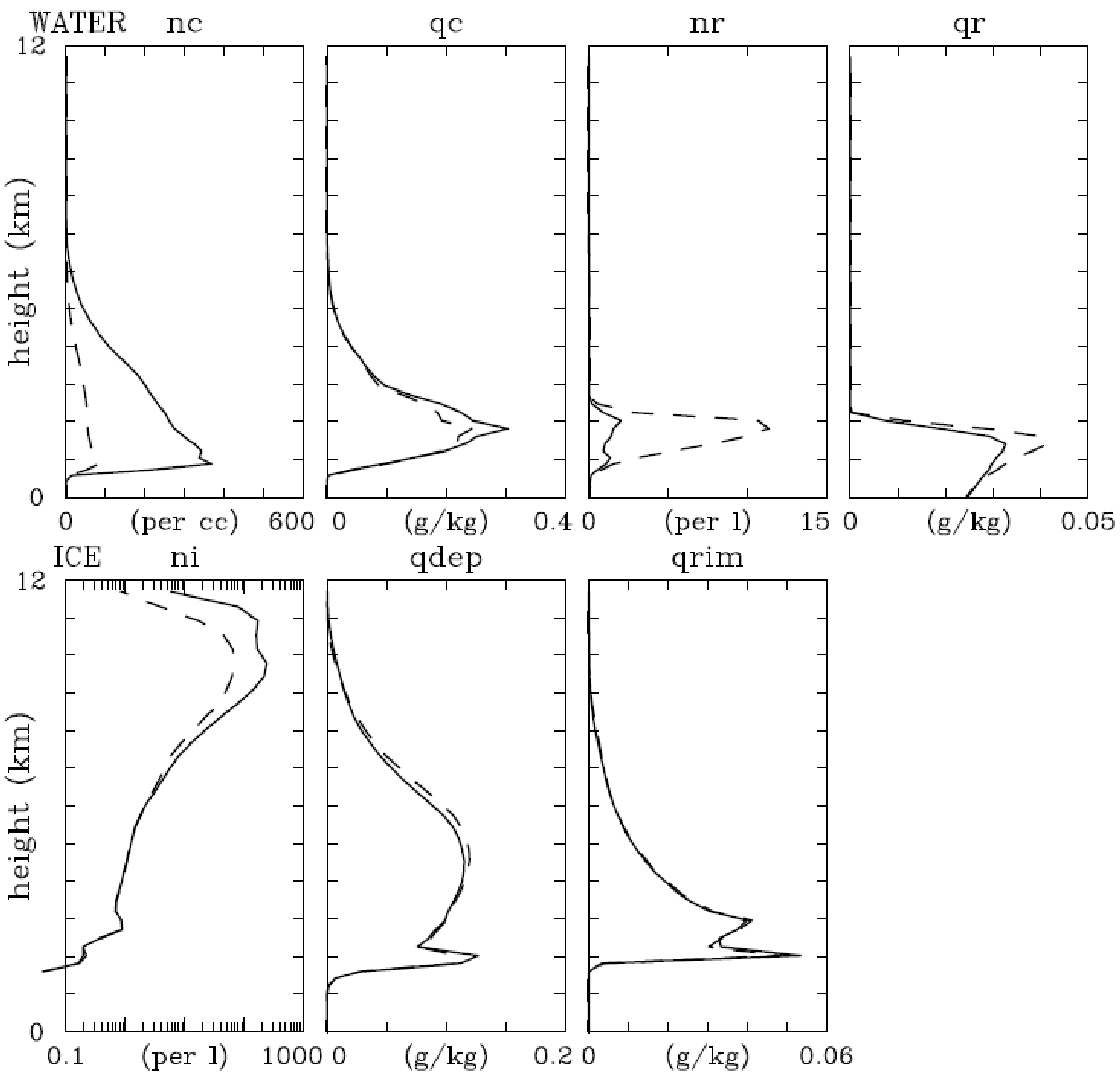
new simulations



Cloud water and drizzle/rain water fields

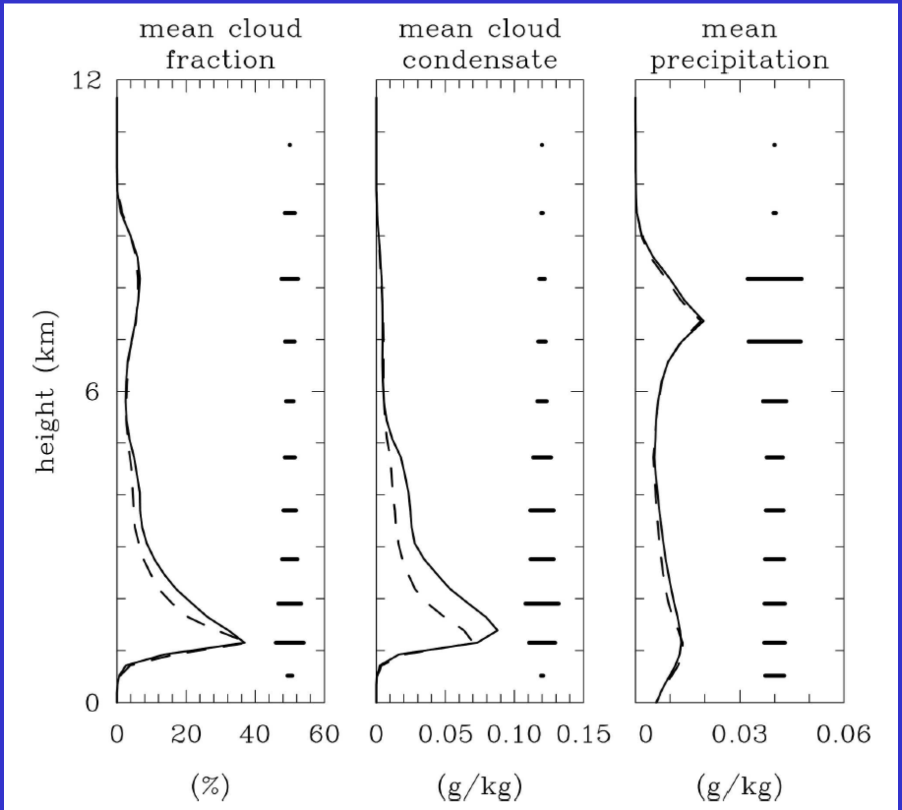
Solid: polluted
Dashed: pristine

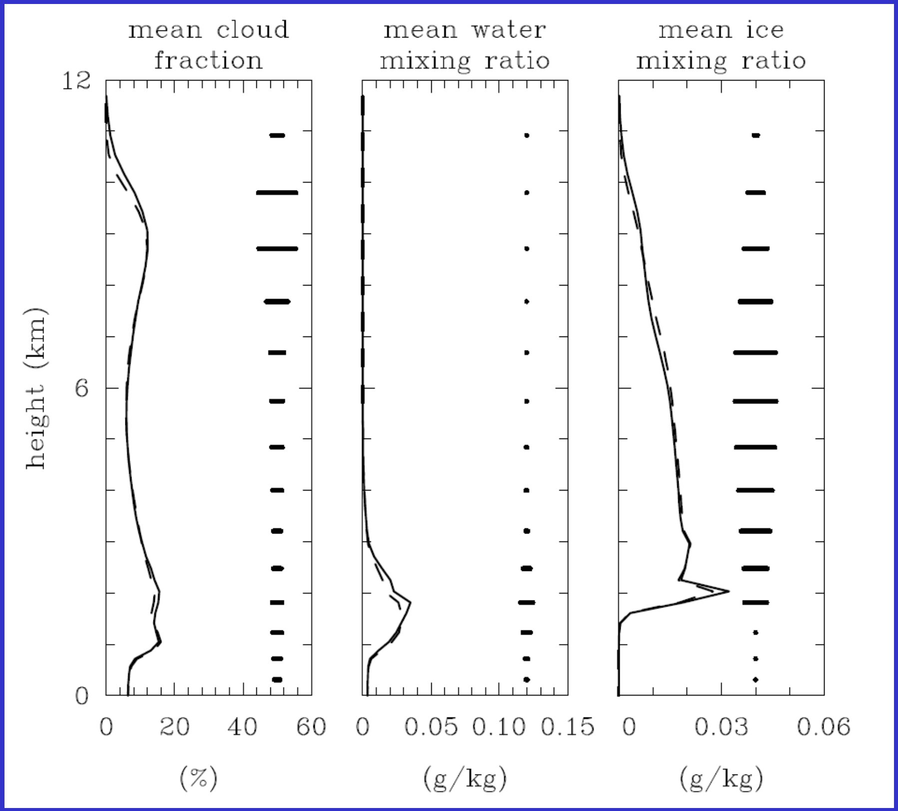
Ice field



Grabowski
***J. Climate* 2006**

new simulations

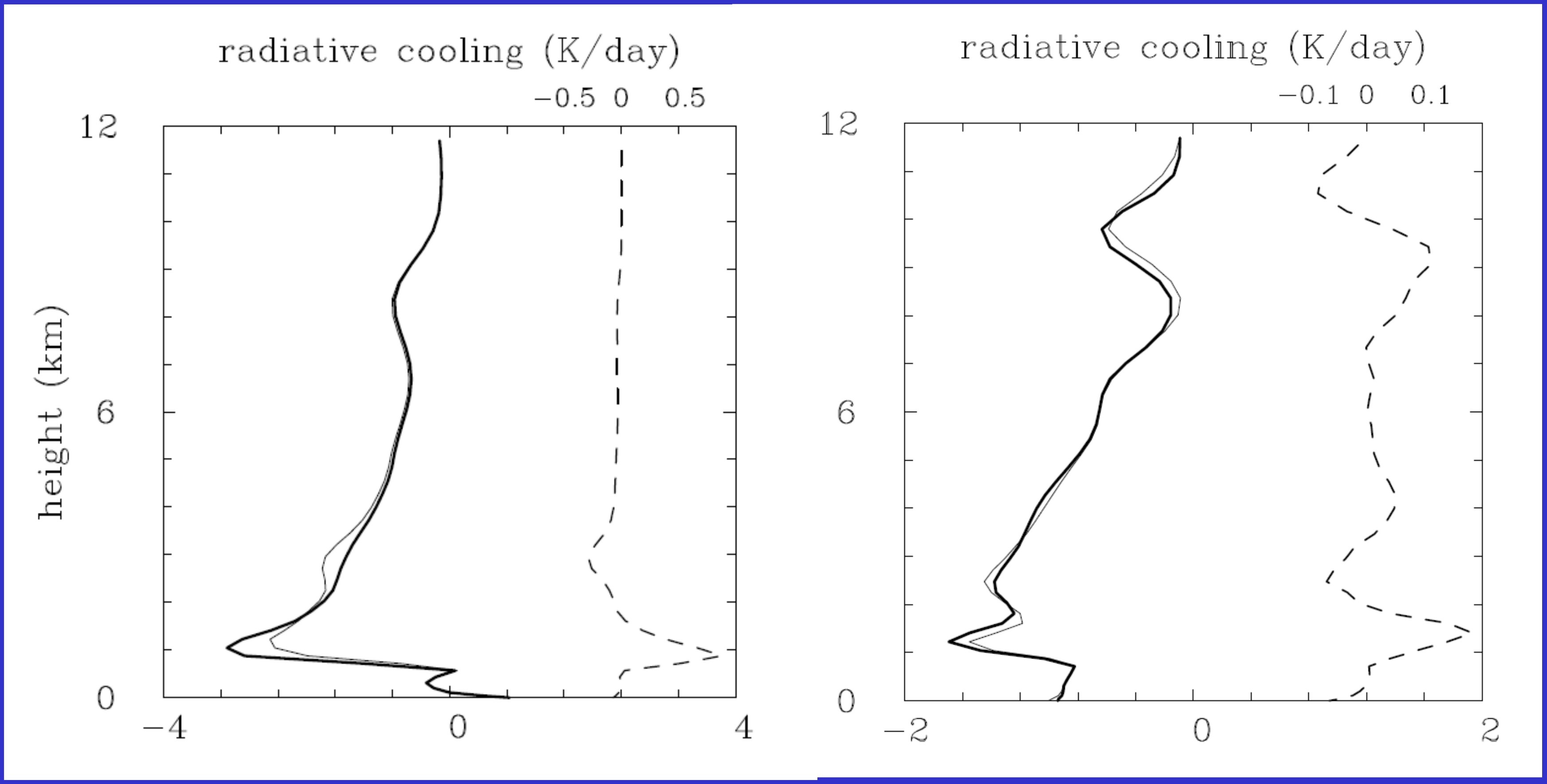




Solid: polluted
Dashed: pristine
Horizontal bars: standard deviation of temporal evolution
(measure of statistical significance of the difference)

Grabowski
***J. Climate* 2006**

new
simulations



Thin: polluted
Thick: pristine
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Microphysics and organized convection:

Can precipitation from organized convection change due to microphysics, without changing the dynamics?

Kinematic model study with a double-moment warm-rain and ice microphysics (Morrison and Grabowski JAS 2007, 2008a, 2008b).

Slawniska et al. (QJ 2009; in press)

IMPACT OF ATMOSPHERIC AEROSOLS ON PRECIPITATION FROM DEEP ORGANIZED CONVECTION: A PRESCRIBED-FLOW MODEL STUDY USING DOUBLE-MOMENT BULK MICROPHYSICS

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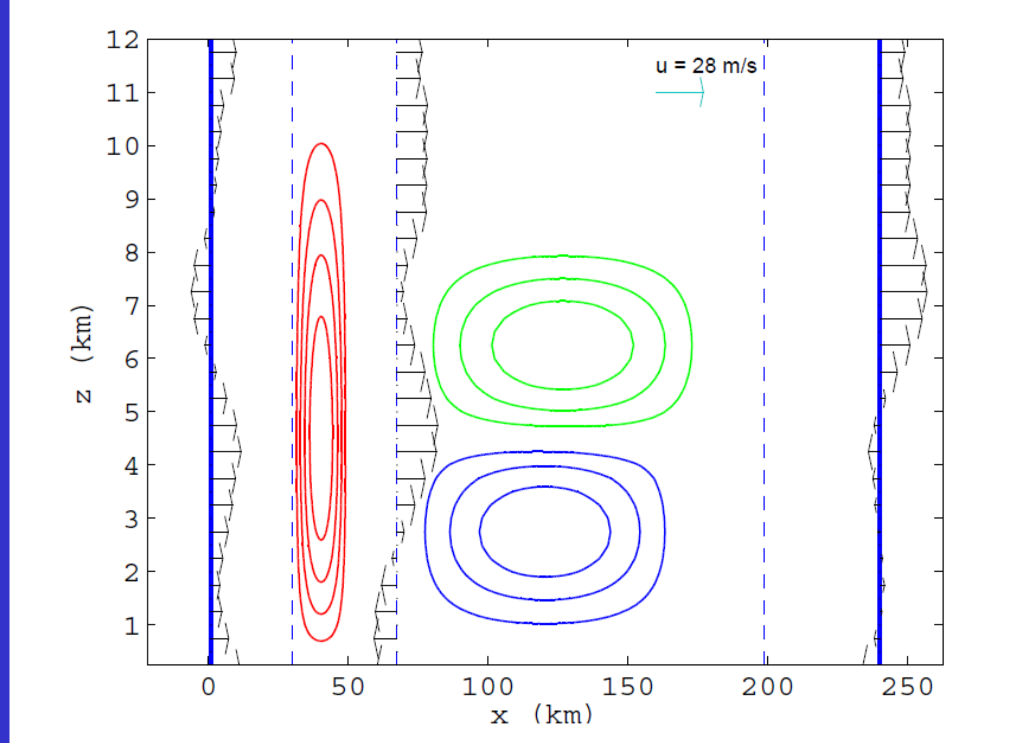
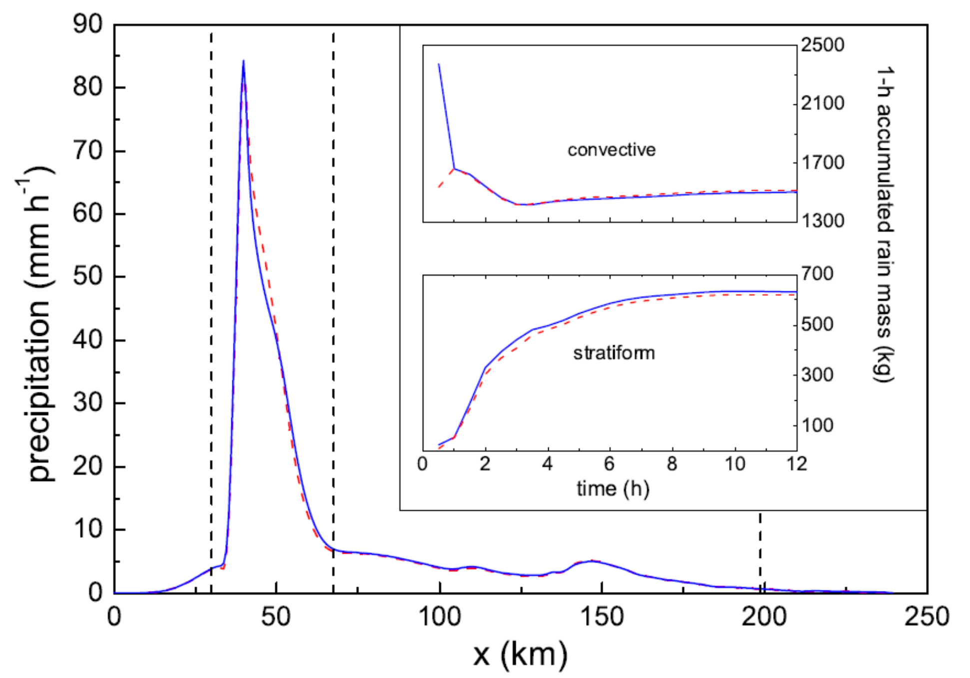
[a] Institute of Geophysics, University of Warsaw, Warsaw, Poland; [b] National Center for Atmospheric Research, Boulder, Colorado



2-moment warm-rain microphysics (4 variables)

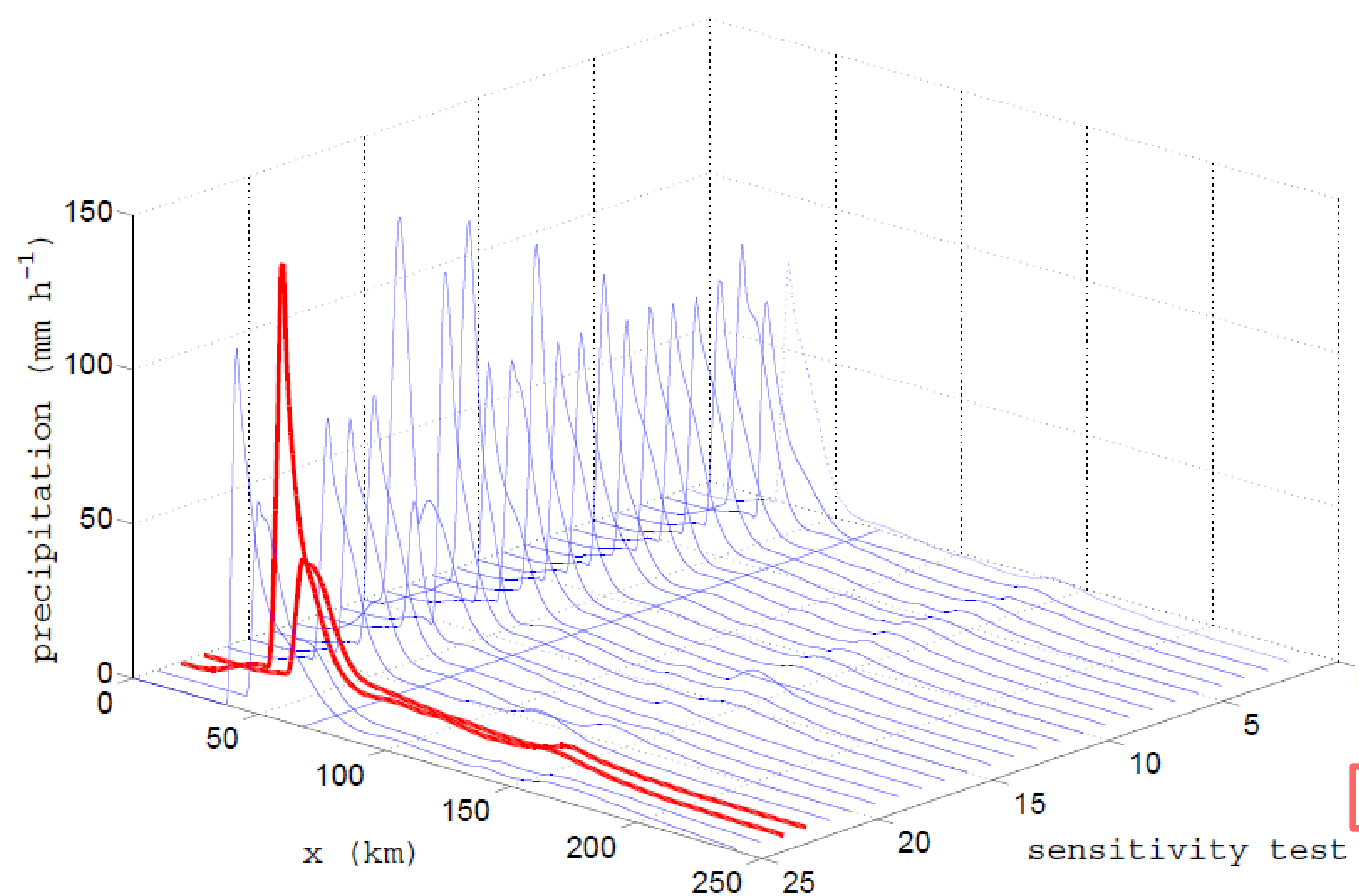
2-moment ice microphysics (3 variables)



PRISTINE/POLLUTED:
droplet concentration in the convective part ~100/1000 cm^{-3}

	simulations	PRISTINE R	POLLUTED R
1	base	2193	2196
2	75% qv	1790	1793
3	125% qv	2589	2590
4	$\theta = \theta - 5K$	2451	2447
5	$\theta = \theta + 5K$	1934	1935
6	10% ice nucleation	2187	2189
7	1000% ice nucleation	2192	2195
8	autoconversion: B1994	2195	2199
9	autoconversion: KK2000	2181	2190
10	smaller coefficient of ice-cloud droplet collision	2194	2195
11	smaller coefficient of ice-raindrops collision	2193	2196
12	enhanced raindrop breakup	2195	2196
13	50% stratiform updraft	2062	2065
14	150% stratiform updraft	2260	2265
15	without downdraft	2973	2979
16	50% downdraft	2561	2561
17	150% downdraft	1874	1876
18	without downdraft + 50% stratiform updraft	2853	2845
19	wider stratiform	2202	2204
20	narrower stratiform	2192	2195
21	stratiform closer to convective	2203	2206
22	70% convective updraft	1403	1406
23	130% convective updraft	3012	3016
24	1000% shear	2037	2042
25	1000% shear + 130% convective updraft	2862	2865

Surface precipitation distribution in all PRISTINE simulations



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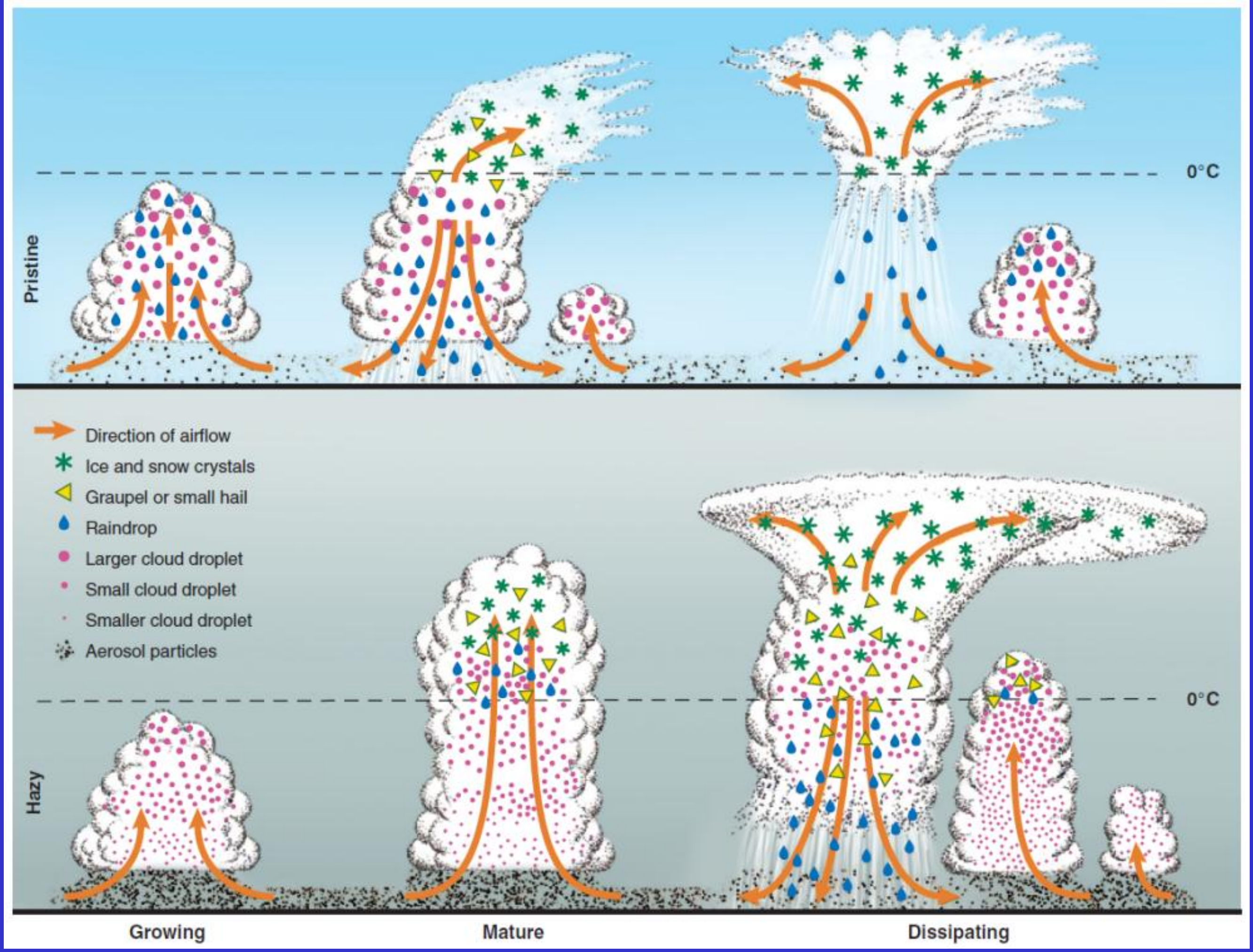
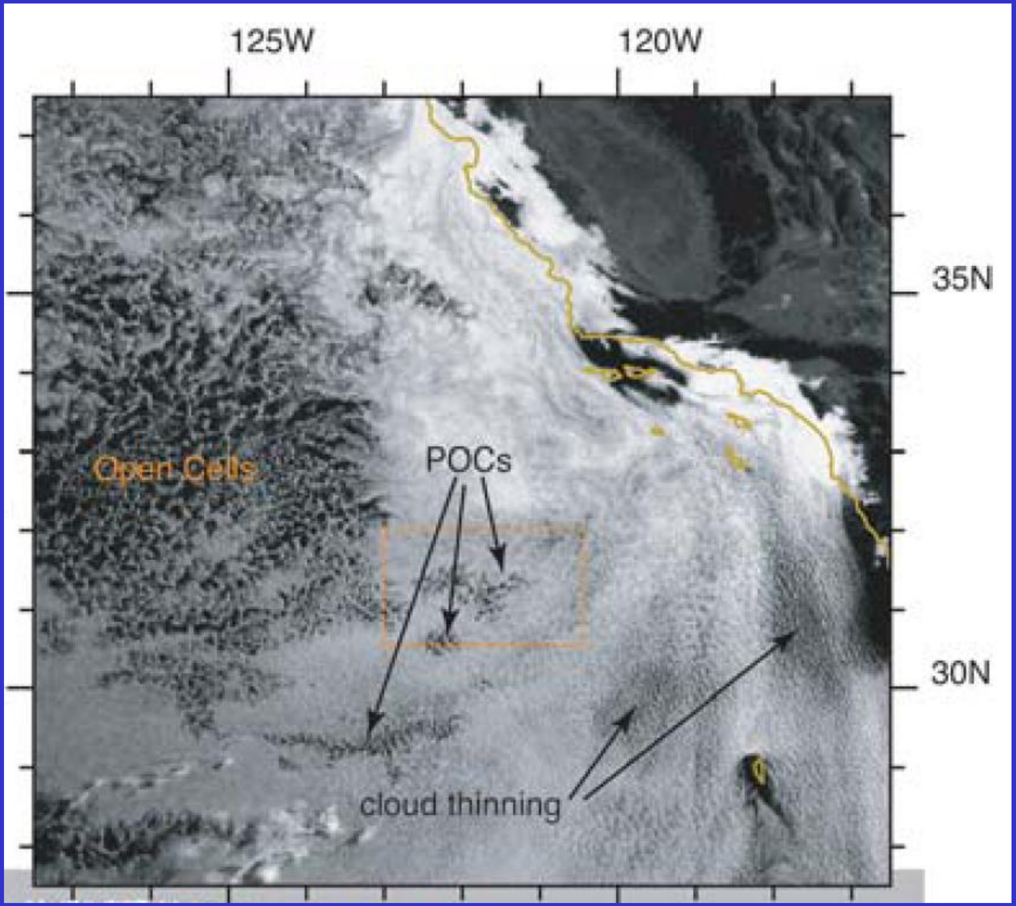
?

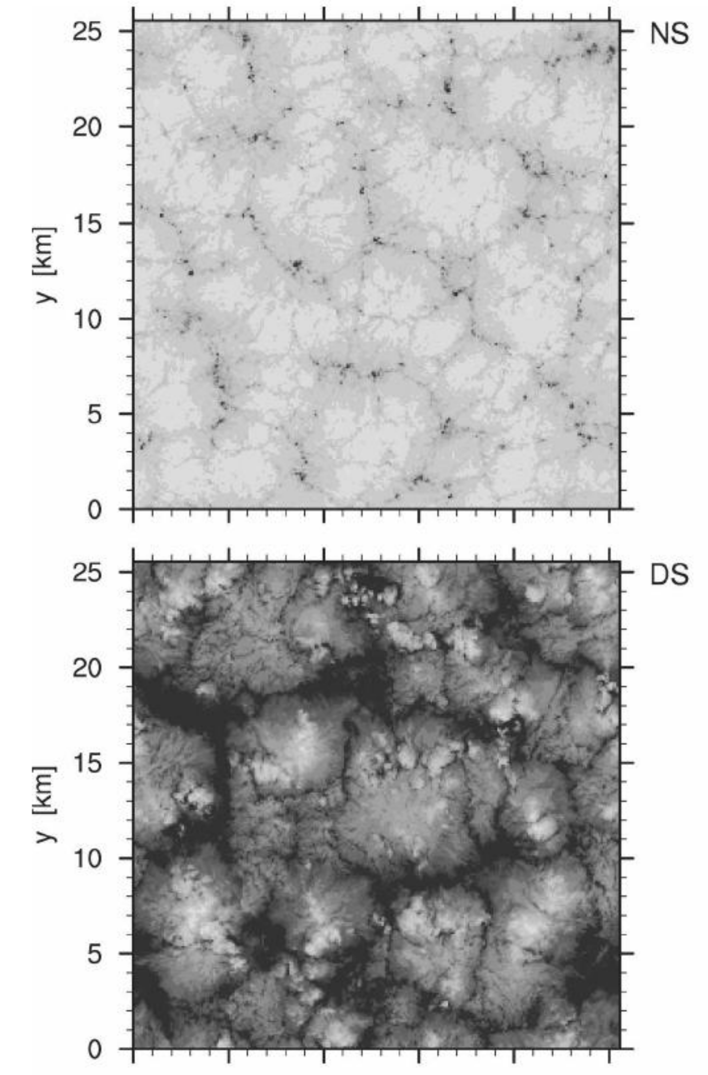


Rosenfeld et al *Science*, 2008



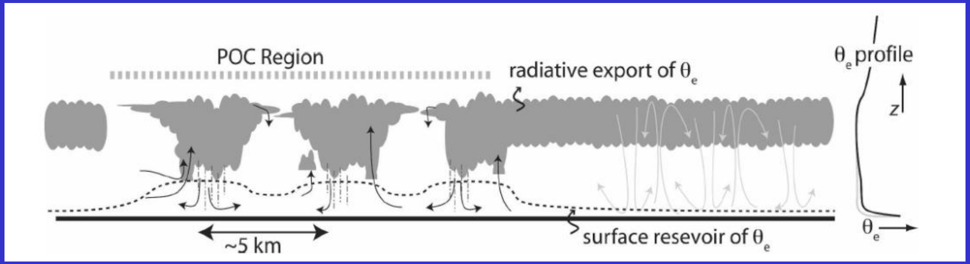
Stratocumulus: *dynamics often slaved to microphysics.*

Fidelity is needed for the microphysics, but also a lot of resolution (LES)…



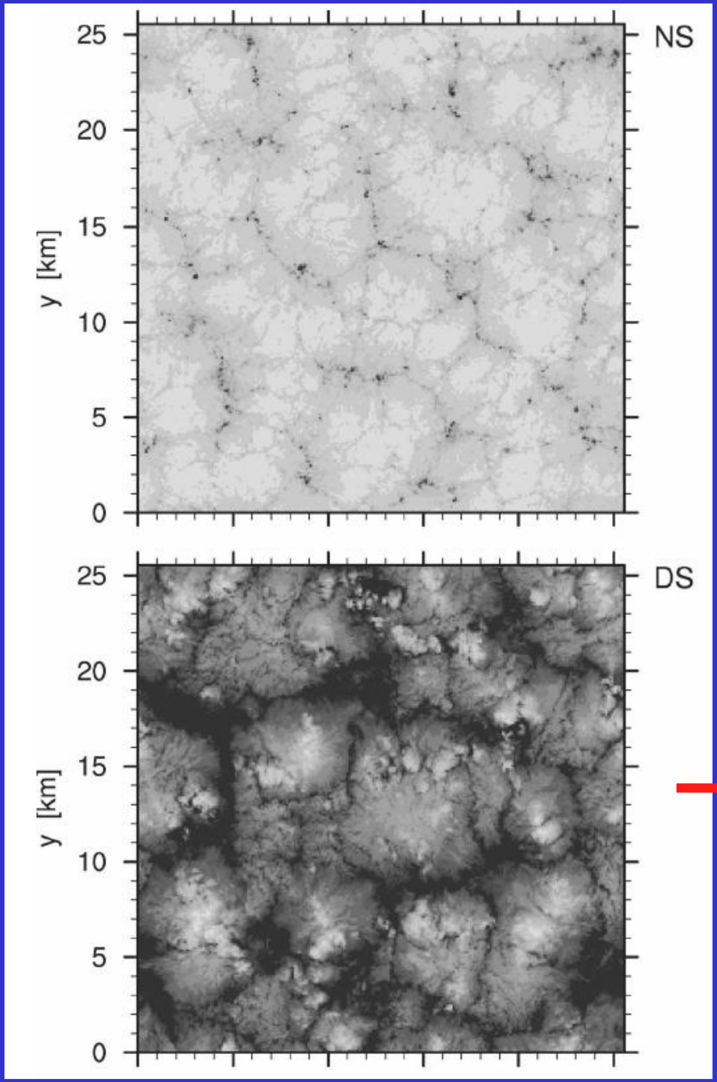
LES of Sc-topped subtropical BL.

*The only difference between the simulations is the assumed concentration of cloud droplets (200 cm^{-3} for NS and 25 cm^{-3} for DS), resulting in **non-drizzling NS case** and **heavily drizzling** (~1 mm/day) DS case.*

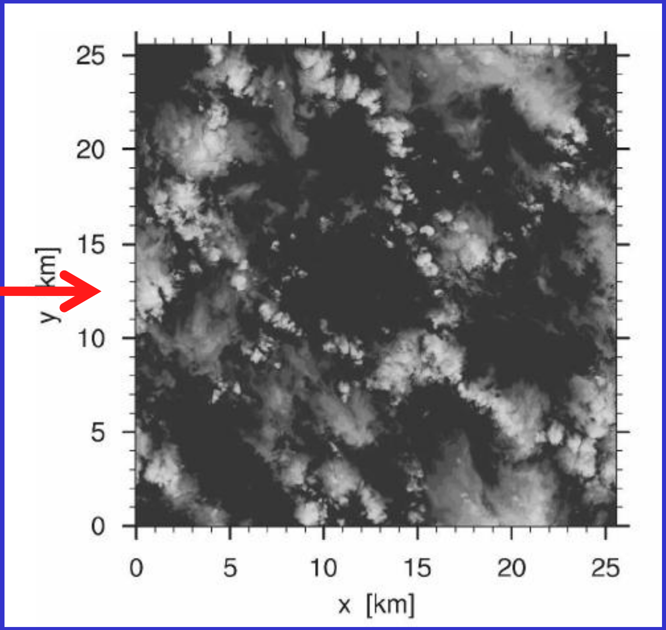


Transition from closed to open cells…

Savic-Jovcic and Stevens *JAS* 2008



after a few
more
hours…



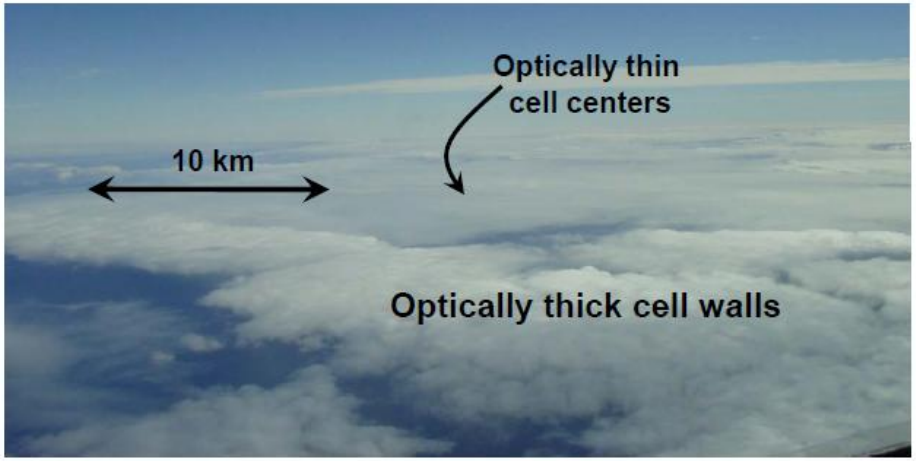
Savic-Jovcic and Stevens *JAS* 2008

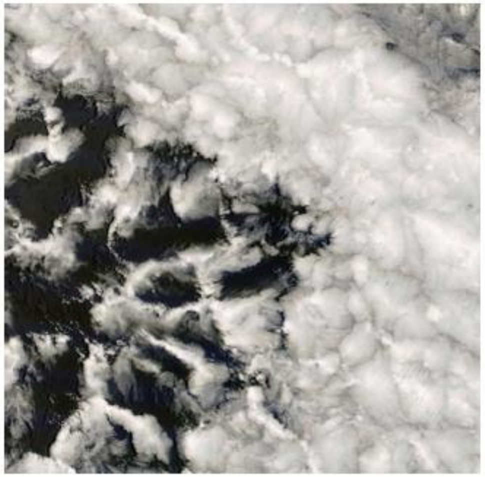
…but Sc not only responses to aerosols, it also very efficiently processes them…

One drizzle drop consists of thousands of cloud droplets, all CCN from these cloud droplets are either combined into a single giant CCN if a drizzle drop evaporates or removed entirely if the drop reaches the surface…

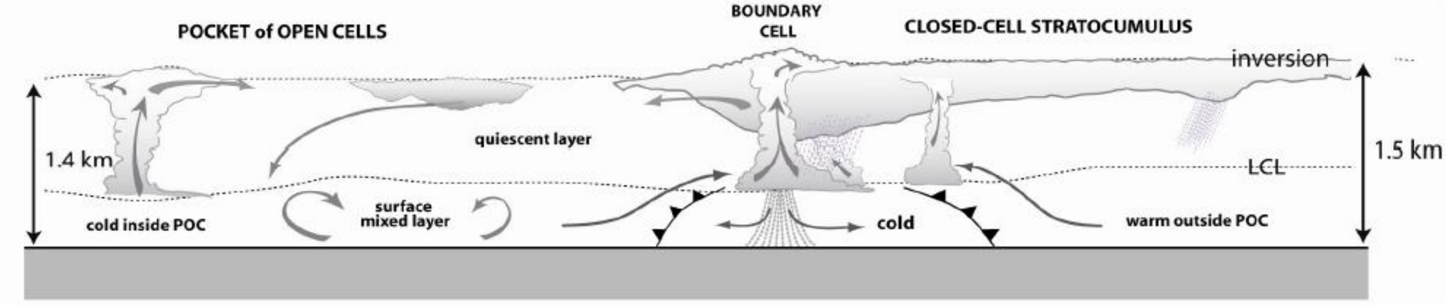
Pockets of open cells (POCs) are manifestation of these poorly-understood interactions.

POC Missions



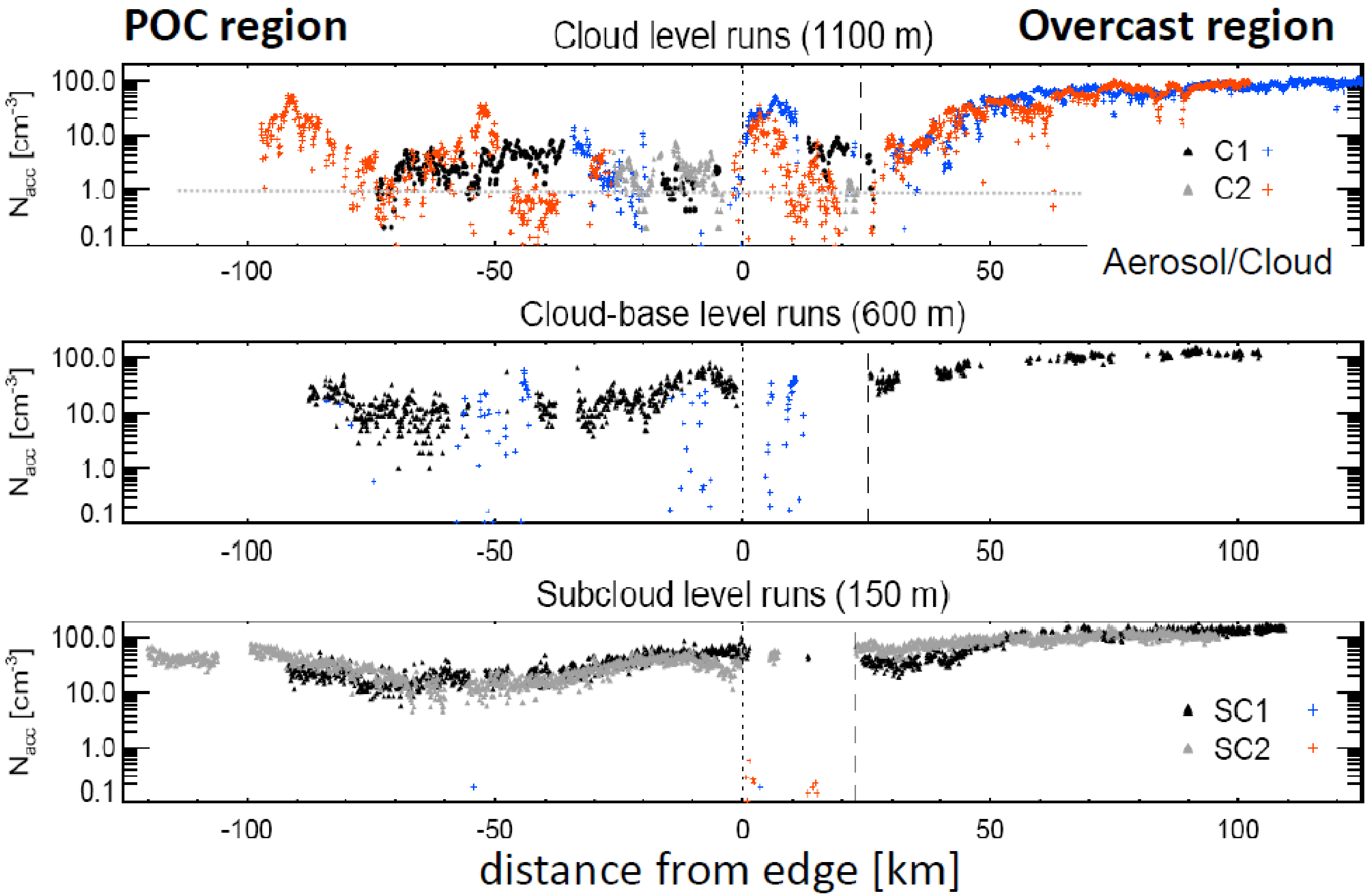


- Lowest CN concentration ever measured
- Remarkable contrasts in microphysics and cloud dynamics across POC boundary [aerosols, drizzle, cloud structure and morphology, CO and O_3]
- Ultraclean clouds in optically-thin cloud centers
- Quasi-linear boundary cells with copious drizzle scavenge aerosols

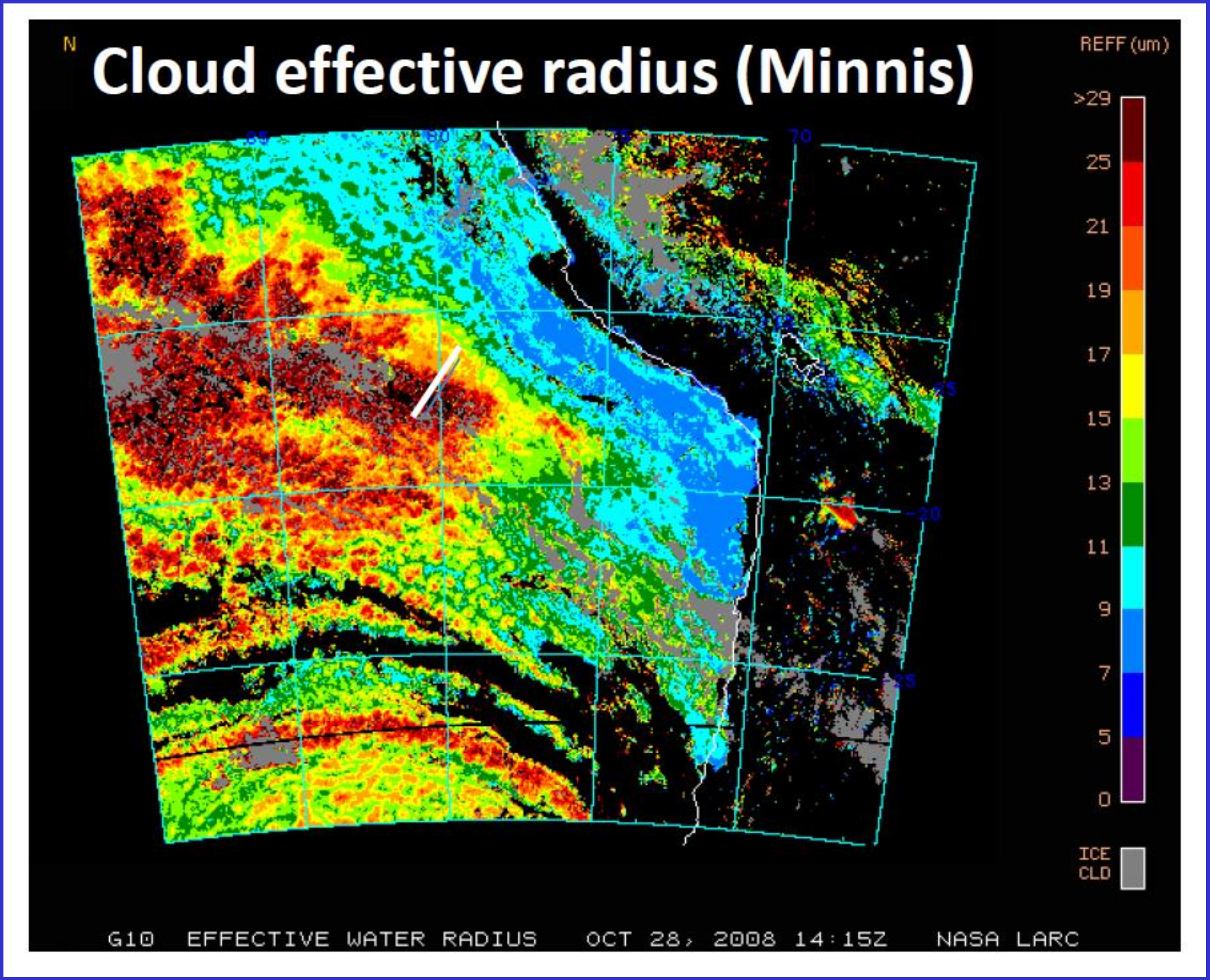


VOCALS campaign (Rob Wood, U. of Washington)

Cloud droplet and accumulation model aerosol concentrations

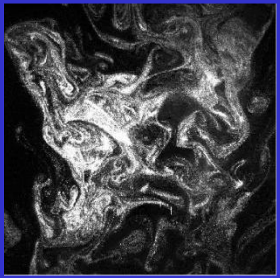


VOCALS campaign (Rob Wood, U. of Washington)



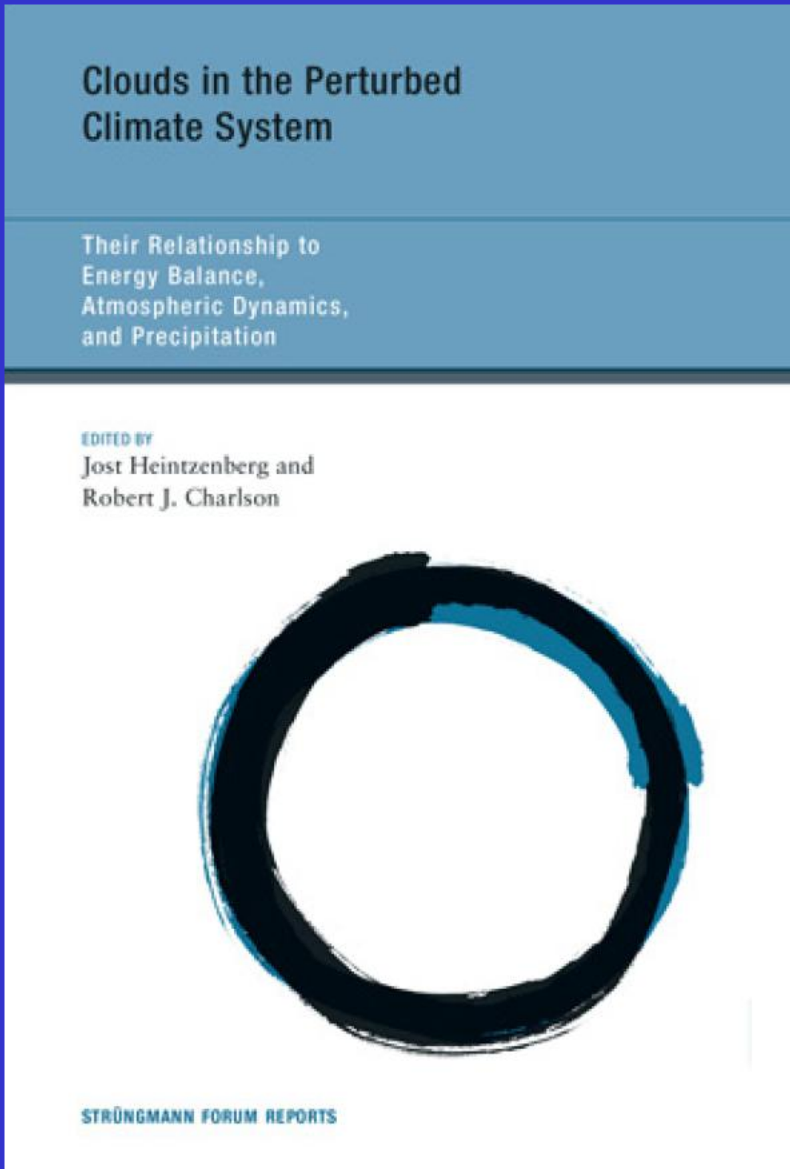
VOCALS campaign (Rob Wood, U. of Washington)

Cloud microphysics have important but poorly understood effects on cloud system dynamics. Simple arguments, supported by modeling, suggests that this impact is most likely the strongest for boundary-layer clouds, which require the highest spatial resolution. The effects on deep convection (and arguably on frontal cloudiness) are unclear .



For indirect (i.e., through clouds) effects of aerosols on climate, contemporary large-scale climate models (i.e., GCMs with tens of km gridlength) are not appropriate (the parameterization^2 problem).

From the cloud-scale processes point of view, efficient algorithms to for aerosol-processing by clouds need to be developed (and tested, e.g., on POCs).



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